Atomic Energy of Canada Limited

THE SIGNIFICANCE OF THE YIELD OF NEUTRONS FROM HEAVY NUCLEI EXCITED TO HIGH ENERGIES

[illegible]

by

W. B. LEWIS

[illegible]

[illegible]

[illegible]

[illegible]

ATOMIC ENERGY OF CANADA LIMITED
Research and Development

DR-24

THE SIGNIFICANCE OF THE YIELD OF NEUTRONS FROM HEAVY NUCLEI EXCITED TO HIGH ENERGIES

by

W.B. Lewis

Chalk River, Ontario
August 25, 1952

Reprinted January 1960

THE SIGNIFICANCE OF THE YIELD OF NEUTRONS FROM HEAVY NUCLEI EXCITED TO HIGH ENERGIES

1. Introduction

The discovery of nuclear fission was hailed as important, because for the first time it became possible on earth to extract nuclear energy on a large scale. On analysis its importance seems to lie in two features: (1) the large energy release of about 200 MeV/fission (1 megawatt day per gram of U-235 fissioned), and (2) the number of neutrons emitted in fission of fissionable nuclei being greater than two.

This second point may need explanation, for while the essential chain reaction requires only that more than one neutron should be released to replace that captured, if there are more than two it is in theory possible not only to sustain the chain reaction but also to form a new fissile nucleus to replace that destroyed. If the number of neutrons released were less than two, the total energy derivable in chain fission from the mineral resources of the world would be not many times the fission energy of the relatively rare isotope U-235, because for each atom of U-235 destroyed it would only be possible to form on the average less than one new fissile nucleus. The fact that there are nuclei such as Pu-239 and U-233 which yield more than two neutrons on fission and are produced each by the capture of only one neutron, makes it possible in theory by the process known as "breeding" to extract fission energy from all the relatively abundant U-238 and Th-232 in the world.

The purpose of this note is to point out the significance of another nuclear reaction phenomenon, which shows an alternative means of extracting energy from all U-238 and Th-232 that does not depend on the existence of U-235 or necessarily require the achievement of breeding. Another aspect of the phenomenon is that the large excess nuclear energy of lead and bismuth (about 140 MeV per nucleus), and possibly also of other abundant nuclei, is added to the total of nuclear energy accessible when technical efficiencies approach more closely the physical limit.

The phenomenon is the high yield of neutrons from heavy nuclei excited to high energies. This yield is known from a number of direct and indirect experiments and substantiated by very simple theoretical correlations. It would be invidious to select any one piece of experimental work as

the discovery of the phenomenon, as it emerges from cosmic ray studies and in particular from the work of many at Berkeley with the 184-inch cyclotron.

Perhaps the earliest published work which reveals it most directly is that of Goeckermann and Perlman, Phys. Rev. 73, 1127 (1948) and of O'Connor and Seaborg, Phys. Rev. 74, 1189 (1948). The former reported that the fission of bismuth by 200 MeV deuterons resulted in fission product yields distributed about a symmetrical peak centred at a mass somewhat below 100. This was explained in terms of a process in which 12 neutrons boil off from the compound nucleus before fission. In a later paper, Phys. Rev. 76, 628 (1949), they give a fission cross-section of bismuth for 190 MeV deuterons of 0.2 barn ± 20%. They state, "It has been calculated (L.W. Baumhoff, private communication) that collisions with 190 MeV deuterons in which less than 100 MeV is transferred occur in only about 25% of the cases." "Of the remaining 75% of the events let us assume that there is a broad maximum probability for excitation at about 120 MeV. The cross-section for such excitations is then about 2 barns which is approximately ten times the observed fission cross-section. Since we assume that any excited nucleus which is degraded to Po-199 has a high probability of undergoing fission, it follows that about 90% of the 2 barns is taken up by reactions in which some charged particles are emitted or which fall short of the necessary neutron emission (12 neutrons) by the emission of high energy neutrons." ... "one would expect to observe fission of bismuth with increasing yields as the projectile energy increases. There is good evidence that this is the case."

O'Connor and Seaborg (loc. cit.) reported the fission of uranium by 380 MeV α-particles yielding fission products showing only a single peak in the region of maximum yield at a mass number less than one-half that of the initial nucleus, although the data were stated to be insufficiently accurate to establish "whether fission is preceded by the emission of a number of neutrons as in the mechanism proposed by Goeckermann and Perlman."

Considerable information on the fission of thorium and uranium induced by high energy charged particles has been given by J. Jungerman, Phys. Rev. 79, 632 (1950), who observed the fission fragment pulses and studied the excitation functions using both the Crocker 60" and the 184" cyclotrons at Berkeley. For U-238, U-235 and Th-232, the fission threshold is at 10 MeV for deuterons and 20 MeV for α-particles at which energies these particles surmount the coulomb barrier. The fission

cross-section rises to 0.6 to 0.8 barn for 7 to 10 MeV increase in particle energy above the threshold. Above 100 MeV the fission cross-sections remain approximately constant up to the limiting energies available, 190 MeV for deuterons and 390 MeV for α-particles. These constant values are

Fission Cross-Sections

	Deuterons	α-Particles
Th-232	1.1 barn	1.4 barn
U-238	1.3 barn	1.6 barn
U-235	1.7 barn	1.4 barn

By selecting a value for the nuclear radius to fit the observations near the threshold, he evaluates by theoretical extrapolation on the Weisskopf model a total reaction cross-section of thorium for α-particles in the range 100 - 400 MeV rising from 3.0 to 3.2 barns.

All this combines to form the picture that these heavy nuclei present a cross-section of 2 to 3 barns to high energy particles, and when excited to high energy, "boil off" neutrons. In the process the fission parameter, Z^2/A, increases and at some stage fission becomes sufficiently probable and takes place, possibly accompanied by a further release of neutrons.

Taking the most simple view suggested by Goeckermann and Perlman that the most probable mode of fission is symmetrical, then these most probable modes would be -

$$_{83}Bi^{209} + {}_{1}D^{2} \longrightarrow 19\ n + 2\ {}_{42}Mo^{96} + 19.8\ MeV.$$

$$_{90}Th^{232} + {}_{1}D^{2} \longrightarrow 26\ n + {}_{46}Pd^{105} + {}_{45}Rh^{103} + 12.3\ MeV.$$

$$_{92}U^{238} + {}_{2}He^{4} \longrightarrow 26\ n + 2\ {}_{47}Ag^{108} + 16.4\ MeV.$$

where the nuclear charge has been divided as symettrically as possible and the masses are those of the most stable nuclei having these charges. The number of neutrons is then given by balancing the mass equation. The energy release is computed from the available mass data: Stanford, Duckworth, Hogg and Geiger, Phys. Rev. 85, 1039 (1952); Duckworth and Preston, Phys. Rev. 82, 468 (1951); Richards, Hays and Goudsmit, Phys. Rev. 85, 630 (1952).

The yields of neutrons arrived at in this way are higher than were found and would only be expected to result from very high energy excitation of the compound nucleus. The neutron yield will be reduced by competition from other modes of de-excitation.

The most probable fission of Bi + D found by Goeckermann and Perlman may be written

$$_{83}Bi^{209} + {}_{1}D^{2} \longrightarrow 12\ n + {}_{42}Mo^{99} + {}_{42}Mo^{100} + 76.6\ MeV$$

and by analogy with this the fission of Th and U may be adjusted to

$$_{90}Th^{232} + {}_{1}D^{2} \longrightarrow 18\ n + {}_{46}Pd^{109} + {}_{45}Rh^{107} + 78.3\ MeV$$

$$_{92}U^{238} + {}_{2}He^{4} \longrightarrow 18\ n + 2\ {}_{47}Ag^{112} + 81.7\ MeV.$$

The latter is quite consistent with the observations reported by O'Connor and Seaborg (loc. cit.).

When, as found in the experiments of Jungerman (loc. cit.), the nuclear excitation is such that fission accounts for a large fraction of the total cross-section, it follows that the neutron yield per excitation will be an even larger fraction of the fission yield of neutrons, because the neutron yield will not be zero in other modes of de-excitation.

Little information is published on the total yields of neutrons, but high yields were found in some unpublished experiments by B.B. Kinsey in 1948 with 90 MeV neutrons from the 184" cyclotron at Berkeley. Briefly expressed, Kinsey's results were that the yield of neutrons from bombarding lead, bismuth, wolfram and tantalum with 90 MeV neutrons is about 7 per collision assuming a cross-section of 1.6 barns, which is about $0.72\,\pi R^2$ where R is the radius of the nucleus. From bombarding thorium and uranium the yield was about 11 and 12 neutrons per collision, assuming a cross-section of 1.8 barns again $\doteq 0.72\,\pi R^2$.

The neutron yield from wolfram bombarded by 157 MeV protons was reported by Skyrme and Williams, Phil. Mag. 42, 1187 (1951). Assuming an inelastic cross-section of 1.55 barns (cf. 1.6 barns assumed by Kinsey for neutrons) they found the number of neutrons per collision was 4.0.

Both Kinsey and Skyrme and Williams were counting only the "evaporation" neutrons emitted isotropically and not the higher energy neutrons projected more in the forward direction. The results are not mutually inconsistent because the mean excitation energy of the evaporating nucleus corresponding to the inelastic cross-sections assumed is not known a priori for 157 MeV protons and Skyrme and Williams derive it from their result as 58 MeV. For excitation by 90 MeV neutrons, Goldberger, Phys. Rev. 74, 1269 (1948), calculated an average excitation energy of a heavy nucleus as 42.5 MeV. Moreover the residual nucleus after proton excitation will have a higher charge and tend therefore to retain more neutrons.

The significance of this phenomenon is that the high yield of neutrons makes possible in theory a cyclic reaction in which electrical power is applied to produce high energy excitation of such heavy nuclei giving a high yield of neutrons. These, in turn, are applied to produce fissionable isotopes. By the chain fission of these isotopes more electrical energy is generated than was initially supplied.

This is a cycle giving a net gain of power and not depending on the natural occurrence on earth of U-235 or other naturally fissionable substance.

2. Requirements for a Practical Power Cycle and for Production of Fissionable Material

The components of the cycle will be grouped as

1. Accelerator
2. Target
3. Chain fission reactor
4. Thermal to electrical power converter.

1. The accelerator will be assumed to be a linear accelerator powered by radio-frequency. All that is relevant to the cycle is

   (1) E_{rf} - the efficiency of conversion of electrical power to radio-frequency power.

   (2) E_b - the efficiency of conversion of radio-frequency power to power in the beam of accelerated particles.

2. The target has the double function of producing neutrons and producing fissionable material.

Relevant are

(1) E_{ne} - fraction of beam energy contributed to inelastic nuclear collisions. In other words, this is the sum of the energies at the time of impact of all primary particles in the beam, which make other than elastic nuclear collisions, expressed as a fraction of the total energy of the initial beam.

(2) Y - yield of neutrons per 100 MeV "inelastic contribution" as just defined.

(3) y_t - yield of atoms of fissionable material per neutron.

3. The chain fission reactor may be characterized by

W - the total energy released per fissionable atom destroyed.

y_r - the yield of new fissionable atoms per fissionable atom destroyed.

4. The thermal to electrical power converter will be characterized by an overall efficiency E_{th} from the heat released in the chain reactor to the electrical power delivered.

Then the electrical power consumed to supply one fissionable atom to the reactor is 100 MeV/$E_{rf} \cdot E_b \cdot E_{ne} \cdot Y \cdot y_t$.

The electrical power derived from a net loss of one fissionable atom in the reactor is

$$E_{th} W/(1 - y_r)$$

For the cycle to yield a net gain of electrical power

$$E_{th} W/(1 - y_r) > 100 \text{ MeV}/E_{rf} \cdot E_b \cdot E_{ne} \cdot Y \cdot y_t \ .$$

If $y_r \geqslant 1$, this is clearly satisfied in the long term and the initial neutrons are required only to start the breeding process.

If $y_r < 1$, the relation may be written

$$E_{th} \cdot E_{rf} \cdot E_b \cdot E_{ne}\, y_t/(1 - y_r) \quad > \quad 100 \text{ MeV}/Y.W \simeq 1/1.6\, Y$$

since $W \simeq 160$ MeV.

Representative values may be assigned to the various parameters, taking into consideration limits set by thermodynamics, particle to circuit coupling, ionization losses and such physical limits, but not limits imposed only by deficiencies of established technology. For example

$$E_{th} = 0.25$$
$$E_{rf} = 0.4$$
$$E_b = 0.4$$
$$E_{ne} = 0.2$$
$$y_t = 1.0$$

$$E_{th} \cdot E_{rf} \cdot E_b \cdot E_{ne} \cdot y_t/(1 - y_r) = 0.008/(1 - y_r) = 0.08$$

if $y_r = 0.9$ and we need $Y > 1/0.128 = 8$ neutrons/100 MeV.

Now it has been seen that a yield of 8 neutrons per 100 MeV "inelastic contribution" is not outside the range which does occur. Provided the values assigned to the parameters can be achieved, the cycle would be possible. This of itself is not necessarily highly significant, for in fact by similar arguments the fission breeding cycle initiated from U-235 can be shown to be possible, yet in view of technological difficulties and high capital costs involved the process has not yet been economically exploited.

It is therefore of interest to make a more practical comparison with alternative means of producing fissionable material. It has been estimated that by natural uranium heavy-water reactors, plutonium can be produced in Canada for about \$200/g. Ultimately it is expected its value may fall as low as \$6/g, but means for producing it at this low cost are not yet established.

On less sure ground the current cost of separated U-235 is estimated at \$60/g.

The cost of producing U-233 may be no greater than for plutonium, but its scarcity due to the small yield obtainable from natural uranium reactors gives it a current value higher than that of plutonium.

If high energy accelerated particles are to be used it is convenient to note that if electrical power were available at 5 mill/kWh, the consumption of 100 MeV per atom of Pu or U-233 produced would contribute $60 per g to the cost of the product.

In terms of the parameters previously introduced, 1 atom of Pu or U-233 is produced per 100 MeV of electrical energy if

$$Y . E_{rf} . E_b . E_{ne} . y_t > 1.$$

With the values previously assigned this requires $Y \geqslant 30$, which is not attainable, but in principle there is no reason why y_t should not be >> 1. It would therefore seem worthwhile to investigate further the attainment of the efficiencies assumed as a means of producing fissionable material and in particular U-233.

3. Discussion of Quantitative Aspects

3.1 Electrical Energy to Fast Particle Energy

Although the theoretical maximum efficiency for generating radiofrequency power from an electron cloud in a magnetron is generally given as about 80%, the overall efficiency seldom exceeds 50% so the assumption of $E_{rf} = 0.4$ is reasonably practical.

The only heavy particle linear accelerator for which data appear to have been published is the 32 MeV proton accelerator at Berkeley. For this the efficiency is very low. For linear accelerators of ~ 10 MeV efficiencies of 40 - 50% have been achieved in the pulses. Although a considerable advance in technique is required it seems that a similar efficiency might be achieved for a deuteron accelerator in the range 200 - 500 MeV. The assumption of $E_b = 0.4$ therefore represents a considerable advance in technique.

It seems at least possible that a higher efficiency $(E_{rf} . E_b)$ could be achieved by using the particle beam itself to convert from D.C. fields supplied locally to radiofrequency power as, for example, the electron beam is used in a Klystron.

3.2 Fast Particle Energy to Nuclear Excitation

In the target the fast particle loses energy by ordinary ionization and atomic collision processes. In heavy elements a high-energy deuteron would lose about 3 MeV/g/cm^2.

If the cross-section for high energy nuclear excitation is 2 barns then the energy loss by ionization and atomic collision per nuclear excitation is 3 MeV/(No. of atoms/g x 2 x 10^{-24} cm^2) $\sim$ 550 MeV.

It follows that a deuteron of even 500 MeV initial energy will contribute only a small part of its energy to nuclear excitation.

A rough evaluation may be made assuming the cross-section for inelastic nuclear collisions is constant and independent of the energy or residual range of the particle so that the number of particles in the beam is attenuated exponentially along the range. The slowing down and stopping of particles by the ordinary ionization and atomic collision processes may be assumed to follow the range-energy relations computed by Aron, Hoffman and Williams, AECU-663. The results of such an evaluation are plotted in Fig. 1 which shows as a function of the initial particle beam energy the fraction possessed by the particles making inelastic collisions at the moment of impact. This energy fraction may be identified with E_{ne} as defined in §2 above.

It will be seen that the value E_{ne} = 0.2 assumed may well be realized in practice. Since, however, the higher values at higher energies in Fig. 1 may lead to lower values of Y, the yield of neutrons per 100 MeV "inelastic contribution" it would be unwise to assume a higher value until it is known that higher beam energies would give a higher value of the product $E_{ne} \cdot Y$.

3.3 Yield of Neutrons per High Energy Excitation

From the reactions quoted in the introduction it seems that whether or not the yield of neutrons tends towards some limit as the nuclear excitation is increased, this limit is certainly greater than 12 neutrons for U and Th. From Kinsey's results the neutron yield for excitations by 90 MeV neutrons reaches values at least as high as 1 per 8 MeV. On this basis 26 neutrons might be expected for excitations of about 200 MeV. If there is any tendency toward a limit this suggests that excitation to energies as great

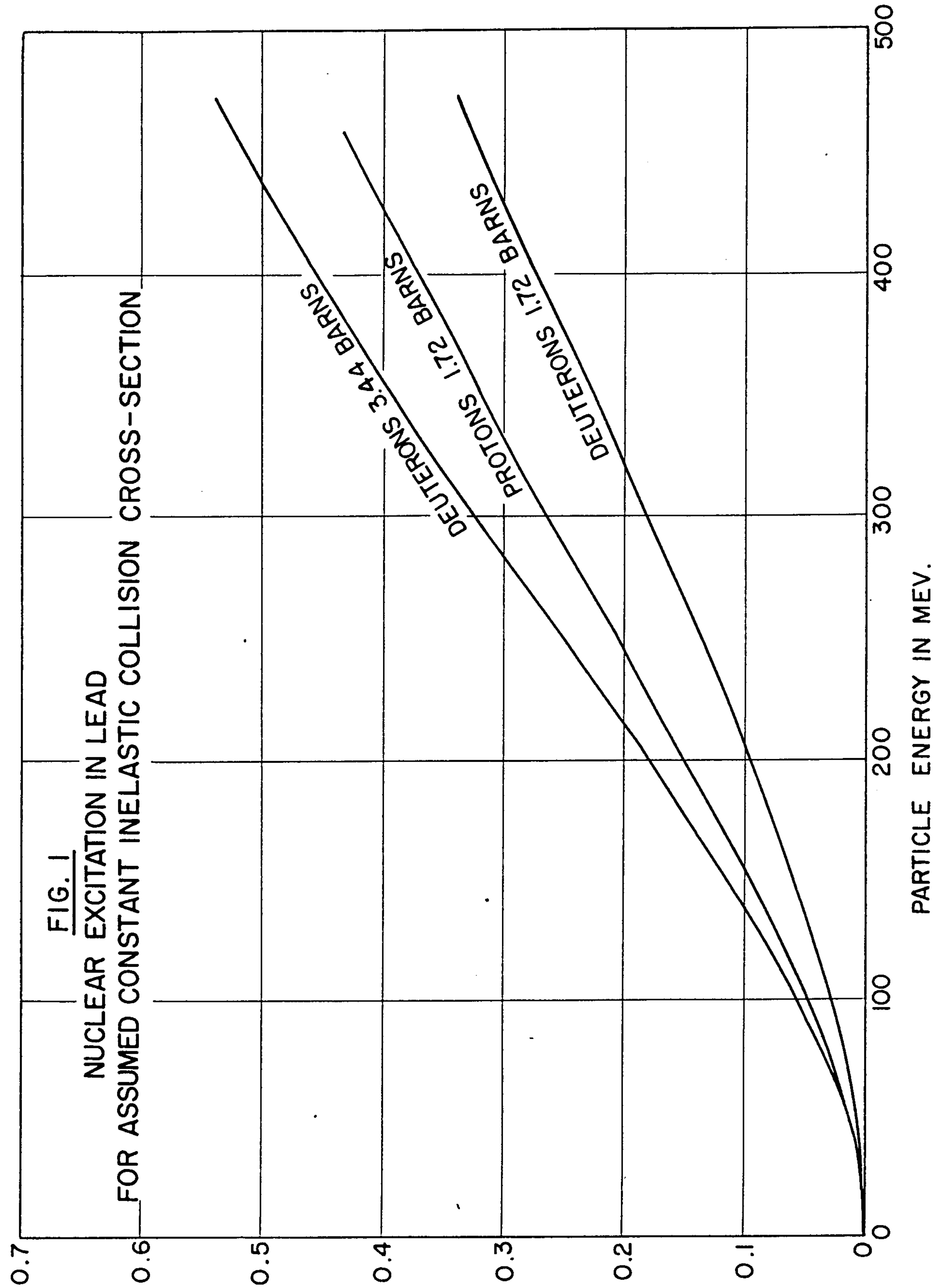

FIG. I
NUCLEAR EXCITATION IN LEAD
FOR ASSUMED CONSTANT INELASTIC COLLISION CROSS-SECTION

as 200 MeV may be wasteful. On the other hand it is possible that excitation to higher energy would yield energetic fragments which could extract further neutrons from other nuclei with which they collide.

Much has been written concerning such high energy excitations of nuclei and it seems to be agreed that the experimental observations are in good accord with the picture developed by R. Serber, Phys. Rev. 72, 1114 (1947), M.L. Goldberger, Phys. Rev. 74, 1269 (1948) and many others. Correlation with experimental data has been made by Bernardini, Cortini and Manfredini, Phys. Rev. 79, 952 (1950) and others, including a recent paper by Bernardini, Booth and Lindenbaum, Phys. Rev. 85, 826 (1952). In a significant fraction of the inelastic collisions of high energy protons with heavy nuclei one or more nucleons have been observed to be ejected with high energies. The evidence suggests that in this phenomenon protons and neutrons are almost interchangeable. If a single high energy nucleon emerges from the nucleus it is almost equally likely to be a proton or a neutron. The mechanism is pictured as a cascade of perfectly elastic collisions between individual nucleons within nuclei. Both protons and neutrons must receive energy greater than their binding energy $\approx$ 6 to 8 MeV in the heavy nucleus if they are to escape. Protons within a nucleus however suffer an added restriction that unless given sufficient energy to surmount the coulomb potential barrier of the nucleus they will not escape. In a heavy nucleus the cascade will be larger, and the energy will be divided among a greater number of nucleons. Finally the excitation energy will be shared among many nucleons and the process will conform to an evaporation model, in which protons, being retained by the coulomb barrier, will be returned to the nucleus, which may still have enough energy to boil off neutrons. It is this process which gives the very heavy nuclei some advantage favouring neutron emission.

In the early stages of the cascade the ejected nucleons may have sufficient energy to initiate cascades in other nuclei. In this secondary cascade process neutrons have an advantage over protons for protons, of energy of 50 MeV or less, lose so much energy by ionization of the atomic electron shells through which they pass that the chance of a further energetic nuclear excitation is small.

For high energy deuterons there is also the deuteron stripping phenomenon to be taken into account, for which heavy nuclei present a cross-section of about 0.3 barn, R. Serber, Phys. Rev. 72, 1008 (1947). This results in fast protons and neutrons which can excite separate nuclei.

For the same energy of nuclear excitation achieved by protons, deuterons, α-particles or other light nuclei, the yield of neutrons in the final evaporation phase may be expected to be slightly less than from neutron excitation because in the final fission fragment each proton binds on the average 1.5 neutrons. Compared with excitation by a neutron, then, for proton excitation at low energies the neutron yield may be expected to be less by 2.5 neutrons (the extra one being the exciting neutron) and for deuteron excitation less by 1.5 neutrons and for α-excitation less by 2 neutrons. This will not be expected to hold for high energy excitation since in the early stages of the cascade the charge of the nucleus will be changed by the ejection of protons and the residual charge will not be the same as that on the initial incident particle and nucleus.

Taking these factors into consideration, the total yield of neutrons in a massive target of heavy nuclei should not be much less than the one per 8 MeV of "Nuclear excitation"* for thorium or uranium or one per 40 MeV of deuteron energy as was assumed. The available information has not yet been evaluated to decide, on this theoretical model, between protons, deuterons or α-particles, but the deuteron appears to have the advantage of an extra loosely bound neutron, and the α-particle has the disadvantage of a much higher (~ 5 times) energy loss by ionization for a given range, which is not likely to be quite counterbalanced by the larger collision cross-section at high energies with heavy nuclei, due not only to its size but also to the lower transparency of nuclei to an α-particle than to single nucleons.

3.4 Yield of Fissionable Atoms Per Neutron

The mean range of a particle in a substance, for which the nuclear capture cross-section is σ, is given by

$$1/(\sigma \times \text{number of nuclei per unit volume}) = A/\sigma N\rho$$

where A = nuclear mass number
N = number of atoms/g atom = 6.02×10^{23},
ρ = density in g/c3 of the absorbing nuclei.

---

* It may be emphasized that "nuclear excitation" energy here used is the mean energy of the nucleon or particle which initiates a nucleon cascade; it must be distinguished from the "average excitation energy" discussed by Goldberger loc. cit. and the "mean excitation energy of the evaporating nucleus" evaluated by Skyrme and Williams loc. cit.

For thorium metal $A/\rho = 232/11.5 = 20.2$

uranium metal $A/\rho = 238/18.6 = 12.8$.

For $\sigma = 2$ barns the mean range in thorium metal would be 16.8 cm and in uranium metal 10.6 cm. For target thickness of this order the problem of heat removal suggests some subdivision by layers of liquid metal coolant and the most obvious suggestion for this is liquid lead or bismuth or mixtures which would contribute to the neutron yield and have a low absorption for neutrons. Selecting from many possibilities the target may be supposed to consist of plates of thorium metal cooled by liquid bismuth-lead alloy flowing between. In this assembly most of the neutron capture would be initially in the thorium. This, however, leads to build-up of U-233 and capture of neutrons by this product. This may result in fission and an increase in the number of neutrons. Moreover thorium is fissionable by fast neutrons and thus may be expected to increase the neutron yield by a small fraction.

To limit escape of neutrons from the target it may be surrounded by an assembly of moderator and fertile material such as thorium or uranium, and in this assembly there may also be some multiplication of the neutrons by the fissionable material there.

From all these considerations it seems that y_t, the yield of fissionable atoms per neutron, may lie anywhere in a wide range depending on requirements. For, considering the fate of neutrons in the target, if we write f_c = fraction captured to make fissionable atoms, and f_f = fraction absorbed by fissionable material, this latter fraction gives rise to ηf_f neutrons. Write $\eta f_f = k$, the reproduction, then the total number of neutrons arising from an initial neutron is $1 + k + k^2 + \ldots = 1/(1 - k)$. The yield of fissionable atoms per initial neutron is then $y_t = (f_c - f_f)/(1 - k))$. This may be re-expressed by writing $f = f_c + f_f$ = total utilized fraction, and noting that $f_f = k/\eta$.

Thus $$y_t = f + k(f - 2/\eta)/(1 - k)$$

from which it is seen that y_t can be $\gg 1$ if k is close to 1 and $f - 2/\eta$ is positive. These are almost identical with the conditions for breeding, and, for example, if $f = 0.95$ and $\eta = 2.35$, then for $k = 0.95$, $y_t = 2.8$, and for $k = 0.99$, $y_t = 10.8$. Moreover, if most of the neutrons are absorbed

while still fast, a higher value for η would be obtained, making y_t still greater. The suggested value of 1.0 in the power cycle or $\gg 1$ in the straightforward production of fissionable material may therefore be accepted as reasonable.

4. Speculations on Lines of Development

In the suggestions above for a power cycle and for the production of fissionable material, these were presented as alternatives to the proposed power-breeder cycle and the operation of natural uranium reactors. This contrast may be misleading and the merits of combinations appear worthy of study.

4.1 Initial Stocks of Fuel for Breeder Reactors

The establishment of a power-breeder cycle requires initially large stocks of fairly concentrated fissionable material. This material may be uranium enriched in U-235 isotope by the diffusion process, or with plutonium derived from the operation of natural uranium reactors.

The thorium - uranium-233 breeder cycle appears to offer some advantages over the uranium-plutonium cycle because the latter is complicated by the formation of Pu-240 which has a very high capture cross-section for resonance and thermal neutrons. The corresponding nucleus in the thorium - U-233 cycle is U-234 which has not so high a cross-section. Moreover the yield of neutrons per thermal neutron absorbed is considerably higher from U-233 than from Pu-239. It may therefore prove easier to design a breeder reactor for U-233 because those neutrons which get reduced to low energies cause less complication.

The problem of building up the required stocks of U-233 to initiate this breeder cycle may well be aided by the high energy process suggested.

4.2 Maintenance of Near-breeder Reactors

In some respects the problems of thermal neutron power reactors appear nearer solution than those of fast neutron reactors, and it may be unwise to accept the fast neutron reactor as the ultimate, despite the advantage it appears to offer in the rate of breeding. It is possible that the thorium - U-233 cycle may breed even in thermal neutron reactors, but if this achievement is missed by a small margin, the defect may be made good by the supply of relatively small amounts of U-233 produced by the high energy process.

4.3 Enriched Reactors

The fast neutron power-breeder reactor may be described as one which operates on a bank-loan of fissionable material. It seems likely that the operation of certain natural uranium reactors might be improved by similar loans, which would be applied to increase the plutonium production. The advantage might be taken in a number of ways such as allowing the reactor to be made smaller, or permitting longer irradiation of each charge of natural uranium, or accepting more depleted uranium in the fuel.

4.4 Combination High Energy and Chain Reactor

It has been seen that the target in the high energy process is essentially a source of neutrons, which may desirably be surrounded by a neutron multiplying assembly like a chain fission reactor. The combination may be regarded as a chain fission reactor enriched by an added source of neutrons. A system in which a small fraction such as 5% of the neutrons are produced by the high energy process might permit cheaper construction of the reactor assembly, and thus be worth adopting.

4.5 Energy from Lead and Bismuth

It was stated earlier that the high yield of neutrons from the high energy excitation of lead and bismuth could add to the accessible nuclear energy about 140 MeV per nucleus of lead or bismuth. It does not seem advantageous to use lead or bismuth instead of thorium or uranium when the latter are available, but used in combination as has been suggested, energy is derived from the lead and bismuth consumed although this is only a small fraction of the energy from the whole system.

If no uranium or thorium were available, the problem of extracting useful energy from lead or bismuth remains formidable. For example, with 100 MeV excitation we may write

$$Bi^{209} + D^{2} + 100\text{ MeV} \longrightarrow 12\text{ n} + Mo^{99} + Mo^{100} + 176.6\text{ MeV}.$$

From the 12 neutrons in the absence of fissionable nuclei, the mean energy release is limited to about 10 MeV per neutron yielding a total of about 300 MeV from the 100 MeV excitation. This gain is insufficient to overcome the losses involved in electrical power generation, but if this problem ever has to be faced it seems likely that better uses for neutrons such as making tritium for thermonuclear reactions would then have been established.

5. Acknowledgment

This report has been written incorporating contributions from B.B. Kinsey, L.G. Elliott, R.E. Bell and H. McManus. Their assistance and much helpful discussion is acknowledged with grateful appreciation.

WBL:dg

W.B. Lewis

August 25, 1952
Chalk River, Ontario

Reprinted January 1960